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14. ABSTRACT

Detection of single or multiple optical subsurface laminar features (e.g., thin layers) in marine waters has many implications on ecologieal studies, management of fisheries, and military applications. This study has four objectives: 1) to corroborate a previous index based on remote sensing reflectance ratio ($R1 = R_{rs}(443)/R_{rs}(490)$) for predicting depth of lidar-derived backscattering layers, 2) to evaluate at what extent these relationships hold in different marine regions, 3) to examine the nature of R1 varisbility in terms of inherent optical properties, and 4) to investigate the influence of water stratification on spatisl distribution of R1 values. Measurements of inherent optical properties (absorption coefficient and scettering coefficient) were obtained from s towed underwater vehicle (Scanfish) in three geographic locations, two in US (Monterrey Bay, MB, and East Sound, ES) and one in Turkish (Black Sea, BS) coastal waters. For each site, case studies were examined based on subsurface optical layers distributed at two different depths (ES: 7 and 20 m, MB: 7 and 20 m, and ES: 15 and 27 m). R1 was theoretically derived from each Scanfish profile end the R1 skewness (ψ) was calculated for each case study. The magnitude of the total absorption coefficient at 675 nm suggested large differences (>100%) in trophic status between the studied areas. However, a common statistical pattern consisting of lower ψ - deeper optical layer was found in all study cases. This variation was explsined by opticel differences above the 'opticline' and mainly related to changes on scattering coefficient of particulates. In general, skewness of R1 was more influenced by $b(440)/a(440)$ rather than by $a(488)/b(488)$ spatial variability. The observed relationships between ψ and the depth of the optical marine layer confirmed a previous finding using airborne lidar and ocean color data. Also, our analysis supports the use of ψR1 to identify the relative vertical position of optical submerged structures in marine environments with vsriable coupling between water stratification and phytoplankton layers.

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Ocean Color Patterns Help to Predict Depth of Optical Layers in Coastal Marine Waters

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Detection of single or multiple optical subsurface laminar features (e.g., thin layers) in marine waters has many implications on ecological studies, management of fisheries, and military applications. This study has four objectives: 1) to corroborate a previous index based on remote sensing reflectance ratio (R1= $R_{rs}(443)/R_{rs}(490)$) for predicting depth of lidar-derived backscattering layers, 2) to evaluate at what extent these relationships hold in different marine regions, 3) to examine the nature of R1 variability in terms of inherent optical properties, and 4) to investigate the influence of water stratification on spatial distribution of R1 values. Measurements of inherent optical properties (absorption coefficient and scattering coefficient) were obtained from a towed underwater vehicle (Scanfish) in three geographic locations, two in US (Monterrey Bay, MB, and East Sound, ES) and one in Turkish (Black Sea, BS) coastal waters. For each site, case studies were examined based on subsurface optical layers distributed at two different depths (ES: 7 and 20 m, MB: 7 and 20 m, and ES: 15 and 27 m). R1 was theoretically derived from each Scanfish profile and the R1 skewness (ψ) was calculated for each case study. The magnitude of the total absorption coefficient at 675 nm suggested large differences (>100%) in trophic status between the studied areas. However, a common statistical pattern consisting of lower ψ - deeper optical layer was found in all study cases. This variation was explained by optical differences above the 'opticline' and mainly related to changes on scattering coefficient of particulates. In general, skewness of R1 was more influenced by $b(440)/a(440)$ rather than by $a(488)/b(488)$ spatial variability. The observed relationships between ψ and the depth of the optical marine layer confirmed a previous finding using airborne lidar and ocean color data. Also, our analysis supports the use of ψR1 to identify the relative vertical position of optical submerged structures in marine environments with variable coupling between water stratification and phytoplankton layers.

INTRODUCTION

A common assumption of remote sensing algorithms based on ocean color sensors is the vertical homogeneity of the water column in terms of optical properties. This approximation is very often not met in coastal and oceanic stratified waters due to the presence of laminar features altering the underwater light field. These submerged layers commonly correspond with thin layers (i.e., <3 m thick), have typically high concentration of dissolved and particulate material with respect to the surrounding medium, and are preferentially developed along the horizontal component (Churnside and Donaghay, 2009). Technologies used to detect vertical location of subsurface optical layers are commonly based on lidar (Light and Range detection) systems (Hoge *et al.,* 1988; Barbini et al., 2003; Churnside and Donaghay, 2009). Unlike these investigations, in a recent contribution, we showed a new approach to discriminate waters with shallow versus deep optical layers based on passive optical measurements (Montes-Hugo *et al.*, 2010). Briefly, the relative distance of the optical layer to the sea

surface is estimated by calculating the third moment around the mean (i.e., skewness or ψ) of a specific remote sensing reflectance ratio ($R1 = R_{rs}(443)/R_{rs}(490)$). As ψR1 decreases the subsurface optical layer becomes deeper. The present study has four main objectives. First, it will test optical relationships found by Montes-Hugo *et al.* (2010) using an alternative approach consisting in independent calculations of ψR1 based on *in situ* measurements of inherent optical properties (IOPs) obtained with an undulating ROTV (remotely operated towed vehicle). Second, it will examine whether the aforementioned approach can be generalized across different marine coastal domains located at different latitudes and characterized by different trophic status. Third, it will investigate the mechanisms explaining ψR1 changes in terms of IOPs modifications. Lastly, it will quantify the influence of water stratification on biological 'layering' and its impact on ψR1 patterns.

METHODS

ROTV surveys

High vertical resolution profiles (0.02 to 0.56 m) of *in situ* optical (i.e., total absorption coefficient of dissolved + particulate matter, *a*, and beam attenuation coefficients, *c*) and CTD measurements were obtained using a ROTV (Seanfish MK II, intelligent undulating vehicle, EIVA, Denmark) in coastal oligotrophic (Black Sea, BS, 41.22-43.70 °N, 28.90-31.26°E), mesotrophic (Monterrey Bay, MB, 36.33-36.83 °N, 121.05-122.85°W) and eutrophic (East Sound, ES, 48.62-48.67 °N, 122.86-122.89°W) waters. The ROTV (0.9 x 0.3 x 1.8 m, length, height, wide) was operated using an undulating mode complemented with a winch to expand horizontal sampling range up to 400 m. The ROTV has a weight of 75 kg, a maximum depth range of 400 m, and a payload of approximately 50 Kg. ROTV data were collected between 14 and 16 pm (local time) and two case studies were selected per study site: 'shallow' (NS) and 'deep' (FS) subsurface optical layer. The ROTV diving 'saw tooth' pattern varied between studied areas (Fig. 1). Depth interval, vertical resolution and horizontal spacing between profiles were 2.8-65, 0.25-0.56 and 370.9 m, for BS, 1.6-48, 0.36 and 268.5 m for MB, and 0.7-22,0.02 and 87.4 m for ES, respectively.

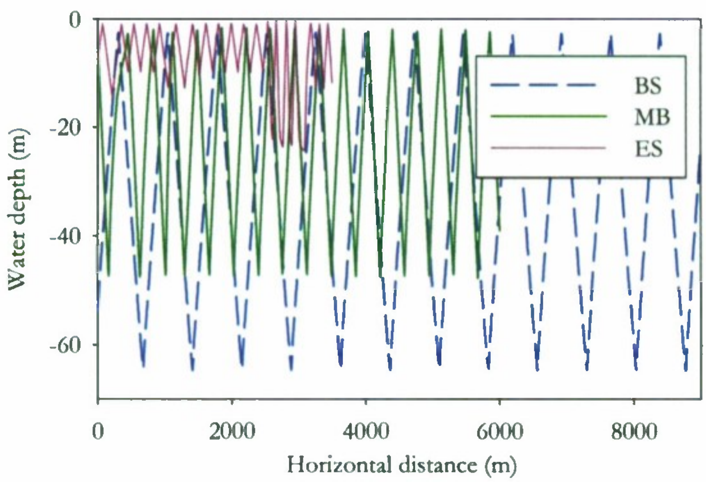

Figure 1. An example of Scanfish MK II dives (ups and downs) in the Black Sea (BS), Monterrey Bay (MB), and East Sound (ES). BS, MB and ES sampling locations had an averaged bottom depth of 125, 120 and 27 m, respectively.

Analysis of optical and CTD profiles

Raw *a*'s and *c*'s coefficients were derived from an ac-9 (WetLabs) at three wavelengths (440, 488 and 675 nm) and corrected by salinity and temperature effects (Pegau *et al.*, 1997; Langford *et al.*, 2001) using CTD (SeaBird 911) measurements. Scattering residuals were removed (Zanaveld *et al.*, 1994). Only descending dives including ROTV-derived IOPs (i.e., total absorption and beam attenuation coefficients), temperature and conductivity were processed and smoothed every 1-m along the vertical. Salinity and seawater density at each depth was derived from CTD variables (i.e., temperature and conductivity without pressure correction) and using the standard UNESCO polynomial equation of state (Millero *et al.*, 1980; Fofonoff and Millard, 1983). For each variable, data gaps were removed by linear interpolation. Missing determinations were more common at finer spatial sampling frequencies (e.g., in ES). The upper mixed layer depth (UML) was computed based on a density difference threshold with depth of 0.015 Kg m^{-4}.

Modeling of ocean color

Spectral remote sensing reflectance ($R_{rs}(\lambda)$) was estimated for each descending profile based on vertical distribution of *a* and *c* values at specific wavelengths. A light propagation model (Hydrolight, Sequoia Inc.) and ancillary data provided from airport-based meteorological stations (Black Sea, www.infospace.ru, Monterrey and Eastsound, www.wunderground.com) were used to simulate $R_{rs}(440)$ and $R_{rs}(488)$. Spatial skewness (ψ) in each experiment was calculated for theoretical $R_{rs}(440)/R_{rs}(488)$ ratios, and vertically-averaged optical properties measured above the subsurface layer (e.g., *a*(675)). Contribution of total scattering ($b = c - a$) with respect to absorption coefficient to ψR1 was also investigated. First optical depth (Z_{OD}) was calculated as the inverse of $K_d(488)$ or the vertical attenuation coefficient of downwelling diffuse light, with $K_d(488) \sim a(488)/\bar{\mu}$ (Mobley, 1994), where $\bar{\mu}$ is the average cosine and was equal to 1 based on cloud cover conditions.

RESULTS AND DISCUSSION

Cross-sections of a(675) suggested that phytoplankton was an important optical component in all subsurface layers under investigation (Fig. 2). Consistent with an increase of solar radiation and freshwater river discharge as the spring-summer season progresses, the main a(675) layer and pycnocline were always deeper during the second experiment in chronological order (e.g., in BS, depth a(675) and UML was 14 and 8.8. m in the 'shallow' case and 28 and 23.2 m in the 'deep' case). In general, drastic vertical changes of a(675) were observed in the vicinity of the pycnocline but during the FS experiment in ES. In this case, it is suggested that phytoplankton communities were not actively growing and were probably sinking as part of a post-bloom stage mainly composed of senescent cells (comm. Pers. Dr. Percy Donaghay). Despite these differences, spatial patterns of ocean color above the sea surface always reflected similar modifications when optical submarine layering became deeper. Indeed, the skewness of R1 switched from positive to negative, as the optical submarine layer was placed farther from the sea surface. Also, these spatial changes in ocean color can be attributed to variability of IOPs in the layer above the main 'opticline' due to the relatively shallow penetration depth of passive sensors in these waters (i.e., Z_{OD} always smaller than depth of subsurface a(675) layer).

In general, skewness of a(675) values measured above the subsurface optical layer was positively related to R1 skewness but in Monterrey Bay experiments (Fig. 3). Likewise, a(675) above and within the submarine layer tended to be negatively correlated (Spearman correlation coefficient up to –0.90 in

NS of ES) but in MB where both quantities were often covarying in a direct way (data not shown). Based on these findings, it is suggested that statistical distribution of phytoplankton cells above the main 'opticline' was linked to variability of IOPs inside the submerged layer and was a major factor explaining spatial patterns of R1. The discrepancy found in Monterrey Bay may be attributed to changes on phytoplankton composition (e.g., replacement of diatoms by dinoflagellates, Moline *et al.*, 2010). However, additional experiments are required to verify this hypothesis.

For each study area, skewness of *b* and *a* at R1 wavelengths was compared between NS and FS experiments in order to elucidate which optical properties and wavelengths were responsible of R1 skewness changes due to depth variation of a single submarine optical layer. In summary, skewness of R1 appeared to be mainly connected to spatial variability of total scattering and presumably backscattering of particulates above the 'opticline'. These optical modifications resembled underwater light field perturbations caused by internal waves (Weidemann *et al.*, 2001). Lastly, ψR1 changes were mainly driven by *b*(440)/*a*(440) rather than by *a*(488)/*b*(488) spatial variability.

Thermo-haline structure as inferred from vertical distribution of seawater density was usually coupled to depth changes of biological properties such as a(675) (Fig. 4). Dekshenicks *et al.* (2001) found that in the majority of cases (i.e., >70%), the depth distribution of optical layers is mainly determined by the water column stratification.

Despite this overall bio-physical relationship, decoupling may occur (e.g., ES in Fig. 4) when optical constituents do not behave as passive tracers (e.g., migrant phytoplankton) or they form aggregates that escape the pycnocline barrier. These ecological scenarios may introduce a large uncertainties when vertical localization of submarine optical layers is based on hydrographic profiles (Zawada *et al.*, 2005). Conversely, ψR1 was very sensitive to vertical changes of subsurface optical layers for a broad range of vertical mixing conditions. Thus, this study supports the generalized use of ψR1 as a non-invasive optical proxy for screening relative depth (e.g., <20 m versus >20 m depth) of thin layers in marine waters having a relatively large water column stability.

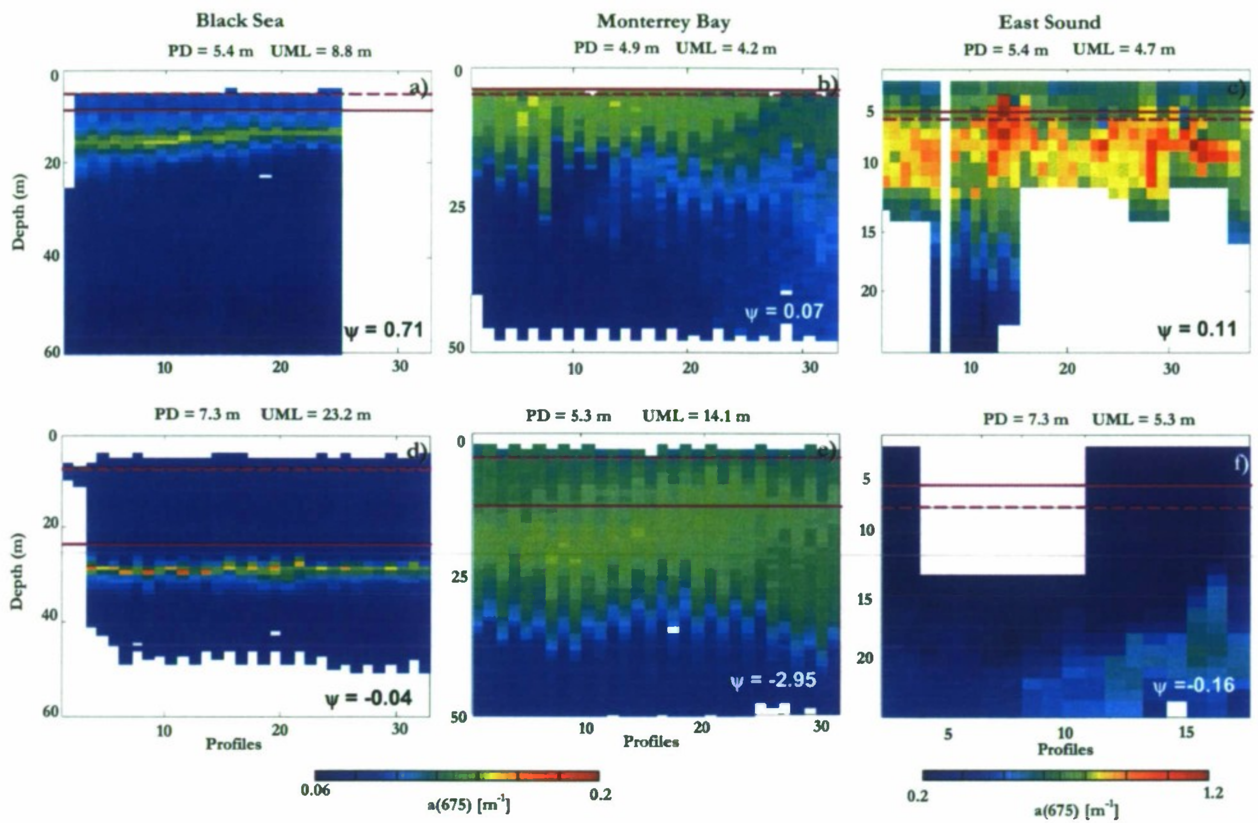

Figure 2. Influence of phytoplankton-derived optical layers on R1 skewness (ψ) estimated from ROTV profiles of IOPs. Depth variations of a(675) for NS (a-c) and FS (d-f) case studies are indicated for Black Sea, Monterrey Bay and East Sound locations. Plots are based on 1-m vertically averaged a(675) data interpolated between ROTV dives (down and up). PD is the inverse of the first optical depth calculated at a wavelength of 488 nm (short-dash horizontal line) and UML is the upper mixed layer depth (horizontal solid line). Not interpolated missing data are depicted in white.

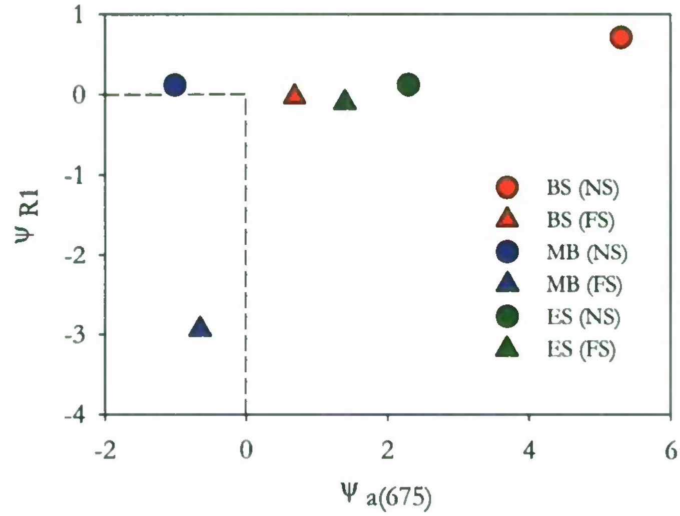

Figure 3. Relationship between spatial patterns of modeled R1 and field measurements of a(675) above the main 'opticline'. ψ is the skewness of the empirical or theoretical data along the ROTV transect. $\psi = 0$ corresponds with a symmetrical Gaussian probability distribution (short-dash lines). BS: Black Sea, MB: Monterrey Bay, ES: East Sound, NS and FS are near-surface and far-from-the surface case studies, respectively.

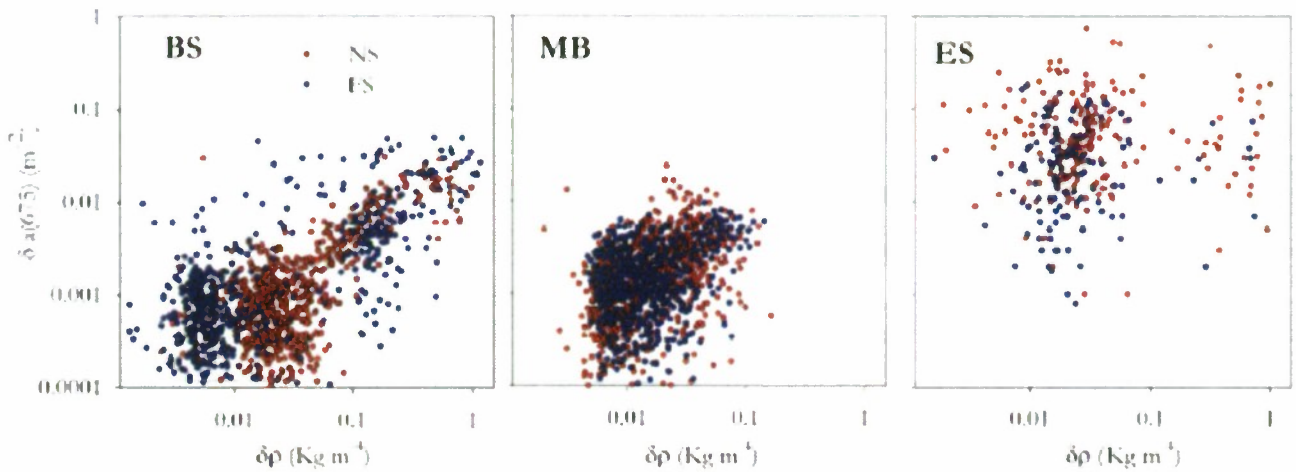

Figure 4. Biological versus physical mechanisms modulating vertical changes of phytoplankton-related optical properties in three coastal stratified environments. Vertical variation (δ) of a(675) and water density (ρ) per meter is plotted in log10 scale. Each data point corresponds to the arithmetic average within 1-m bin. Ascending and descending ROTV measurements are included. BS, MB, ES, NS, and FS acronyms are defined in Figure 3.

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